

Microgravity Investigation of Crew Reactions in 0-G (MICR0-G)

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Final Report

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Abstract

*There is a need for a human factors, technology-based bioastronautics research effort to develop an integrated system that reduces risk and provides scientific knowledge of astronaut-induced loads and motions during long-duration missions on the International Space Station (ISS), which will lead to appropriate countermeasures. The primary objectives of the **Microgravity Investigation of Crew Reactions in 0-G (MICRO-G)** research effort are to quantify astronaut adaptation and movement as well as to model motor strategies for differing gravity environments. The overall goal of this research program is to improve astronaut performance and efficiency through the use of rigorous quantitative dynamic analysis, simulation and experimentation.*

The MICRO-G research effort provides a modular, kinetic and kinematic capability for the ISS. The collection and evaluation of kinematics (whole-body motion) and dynamics (reacting forces and torques) of astronauts within the ISS will allow for quantification of human motion and performance in weightlessness, gathering fundamental human factors information for design, scientific investigation in the field of dynamics and motor control, technological assessment of microgravity disturbances, and the design of miniaturized, real-time space systems. The proposed research effort builds on a strong foundation of successful microgravity experiments, namely, the EDLS (Enhanced Dynamics Load Sensors) flown aboard the Russian Mir space station (1996-1998) and the DLS (Dynamic Load Sensors) flown on Space Shuttle Mission STS-62. In addition, previously funded NASA ground-based research into sensor technology development and development of algorithms to produce three-dimensional (3-D) kinematics from video images have come to fruition and these efforts culminate in the proposed collaborative MICRO-G flight experiment. The required technology and hardware capitalize on previous sensor design, fabrication, and testing and can be flight qualified for a fraction of the cost of an initial spaceflight experiment. Four dynamic load sensors/restraints are envisioned for measurement of astronaut forces and torques. Two standard ISS video cameras record typical astronaut operations and prescribed IVA motions for 3-D kinematics. Forces and kinematics are combined for dynamic analysis of astronaut motion, exploiting the results of the detailed dynamic modeling effort for the quantitative verification of astronaut IVA performance, induced-loads, and adaptive control strategies for crewmember whole-body motion in microgravity. This comprehensive effort, provides an enhanced human factors approach based on physics-based modeling to identify adaptive performance during long-duration spaceflight, which is critically important for astronaut training as well as providing a spaceflight database to drive countermeasure design.

Introduction

The Microgravity Investigation of Crew Reactions in 0-G (MICR0-G) flight experiment focuses on understanding the mechanisms by which astronauts adapt to, move about, and develop motor strategies for differing gravity environments. The overall goal of this research program is to improve astronaut performance and efficiency through the use of rigorous quantitative dynamic analysis, simulation and experimentation. This goal will be achieved by studying the neural adaptation process that permits astronauts to efficiently perform movements across a spectrum of gravity (*i.e.*, microgravity, Moon, Mars, and Earth). We will quantitatively characterize (*e.g.*, used muscle groups and required joint torques) the skills and movement strategies that veteran astronauts use to move their bodies through altered gravity environments and how the motor control strategies develop over time during long-duration spaceflight missions. In doing so, we hypothesize that a single adaptation process can be identified, which is responsible for the adaptation seen across the entire gravity spectrum.

The MICR0-G research effort investigates the locomotor skills required to move one's entire body from place to place while on orbit. Observing astronaut skills and performance requires a highly accurate data acquisition system. The MICR0-G sensors and accompanying kinematic video system will provide a complete picture of the astronauts' control strategy from calculated joint torques that can be computed from the coupled kinetic and kinematic measurements (based on CCD cameras which enable noninvasive motion capture). Knowledge of the joint torques will permit a detailed analysis of the joint and musculoskeletal dynamics employed to execute motions as well as the neural adaptation process in altered gravity. Understanding the adaptation process will facilitate the development of new training techniques that encourage astronauts to develop appropriate movement strategies prior to exposure to the altered gravity environment and during transition to another gravitational environment. Ground experiments will be conducted as part of the MICR0-G flight experiment to test these new training techniques underwater and on the KC-135 microgravity aircraft. Continued scholarly collaborations between the MICR0-G team, NASA and international researchers (Italian and Russian) will assure widespread data dissemination and feedback.

Background and Hypotheses:

One of the key challenges to living in space is locomotor function in a microgravity environment. Moving from place to place within the spacecraft requires an altered set of control strategies than are applicable for 1-G. Fortunately, astronauts have demonstrated their ability to adapt their locomotor control strategies to fit the needs of microgravity operations [Newman et al., 2000]. However, during the period of time before astronauts completely adapt to this new environment (~2-4 weeks) the productivity of the astronauts is severely limited (as evidenced by recent research using instrumented hand and foot restraints [Newman et al., 2001, 1999]). Furthermore, while the newly adapted movement strategies are typically appropriate for the microgravity environment, they are not suitable for partial gravity environments, possibly forcing a re-adaptation period upon return to Earth or arrival at another planet [Baroni et al., 2001]. For planetary exploration missions, where astronauts are expected to explore a gravity environment immediately after a lengthy (> 6 months) microgravity spaceflight, this re-adaptation phase could significantly affect the astronauts' ability to perform their mission and science duties. Understanding the characteristics of the locomotor control strategies adopted by veteran astronauts as well as the adaptation or skill selection process used to arrive at them could provide insight into new training techniques and countermeasures intended to accelerate the adaptation and re-adaptation.

***Hypothesis #1:** A single adaptation mechanism governs human locomotor control strategies across a spectrum of gravity environments in a manner similar to that predicted by classical adaptive control laws. Furthermore, this adaptation mechanism is realizable given the physiology of the human musculo-skeletal and central nervous systems.*

Part of hypothesis #1 tests whether or not human locomotor control follows that of conventional adaptive control (a computed torque model by construction, as opposed to an equilibrium point model). This hypothesis may be proven false, possibly providing evidence for the equilibrium point control model in the context of human locomotor adaptation to spaceflight. Thus, both computed torque and equilibrium point models will be considered in this research to determine the appropriate model to describe this adaptation.

Hypothesis #2 tests the existence of a phenomenon known as multi-adaptation*, based partially on the outcome of testing hypothesis #1.

Hypothesis #2: *Given exposure to a particular gravity environment, humans will retain the adapted locomotor control strategies for multiple months of constant exposure to a different gravity environment, providing evidence of multi-adaptation through either new skill invocation or the retention of multiple control gain sets.*

With the insight gained from the results of hypotheses #1 and #2, addresses the countermeasure development aspect of the MICR0-G research effort.

Hypothesis #3: *Locomotor adaptation to microgravity and partial gravity can be accelerated by encouraging subjects to use similar joints and muscle groups during training and on-orbit as well-adapted veteran astronauts.*

* The term *multi-adaptation* has been derived from the term *dual-adaptation* to denote adaptation to more than two different environments at once.

Materials and Methods

Kinetic and kinematic data will be gathered from subjects using the MICRO-G force-moment sensors and the kinematic video system. The MICRO-G force-moment sensors are being developed to look and feel like regular crew restraints. Each sensor will be able to collect force and moment data at a rate of 250Hz and store the data in an on-board hard drive. The kinematic video system and accompanying software will be able to measure the subjects' joint angles using only 2 video cameras while not requiring any distinctive markings on the subjects' limbs. Figure 1 illustrates a preliminary design of the force-moment sensors to be used for the MICRO-G experiment.

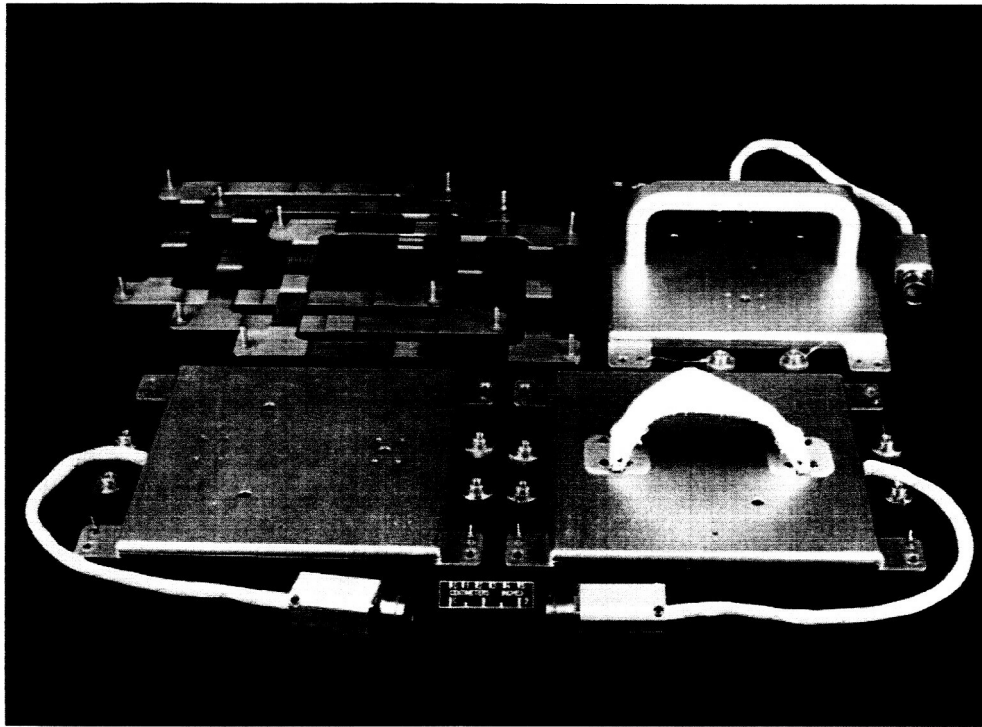


Figure 1: A preliminary design for the MICRO-G force-moment sensors.

Full body motion experiments will be carried out in a 1-G lab setting prior to flight and immediately after flight, on the KC-135 microgravity aircraft and during spaceflight on the ISS. The selected body motions will include several push-offs and landings using both arms and legs to illustrate the types of motor strategies used by astronauts as they adapt to their new environment. Figure 2 illustrates one such body motion as well as the proposed placement of sensors and video cameras for proper data collection.



Figure 2: *A crewmember performing a push-off and landing during a MICRO-G experiment session.*

During the spaceflight experiments on the ISS, kinematic and kinetic data will also be gathered from subjects during their regular daily activities. Crewmembers will be encouraged to use the MICRO-G sensors as regular crew restraints while they move about the cabin. Figures 3 and 4 illustrate possible scenarios of subjects using the MICRO-G sensors as if they were regular crew restraints.

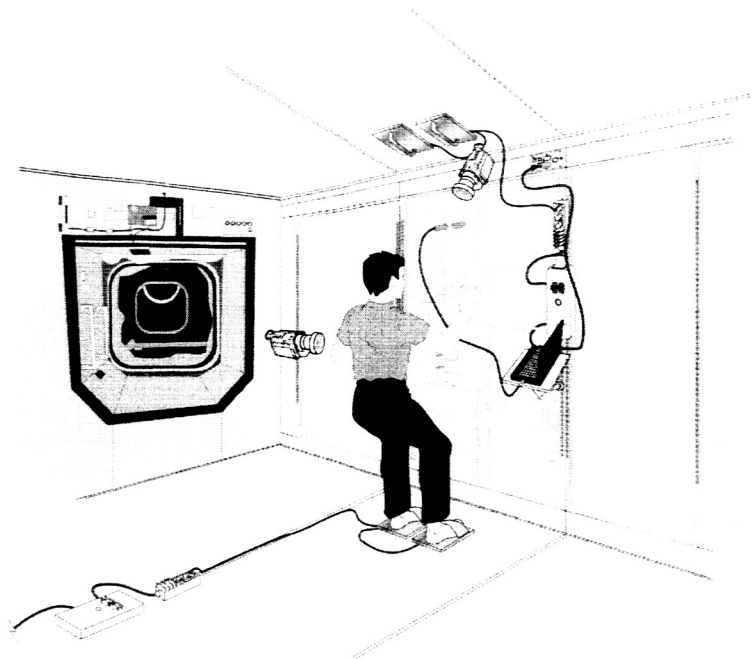


Figure 3: A crewmember working on an experiment rack while secured into the MICRO-G foot restraints.

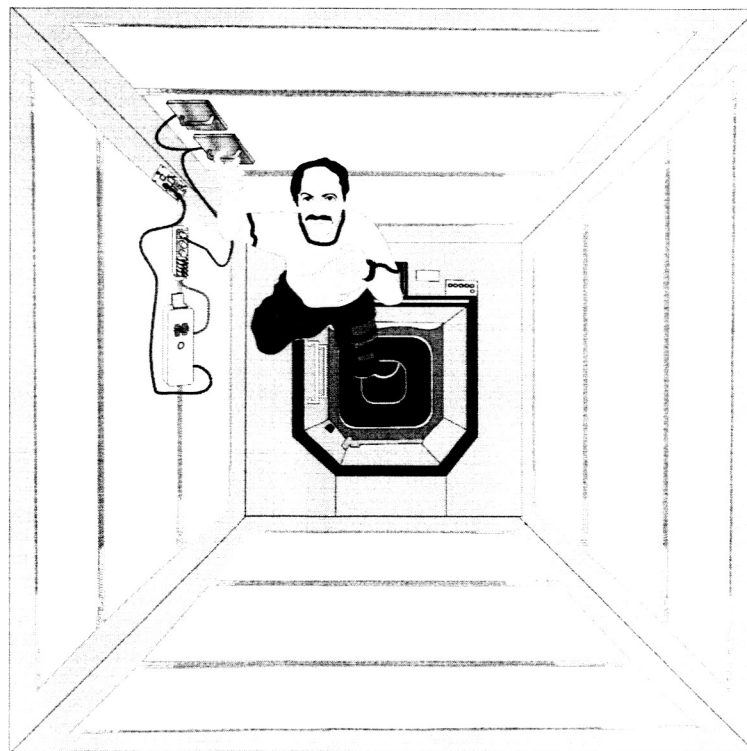


Figure 4: A crewmember using a hand hold sensor to pull himself through the cabin.

Preliminary Results and Discussion

Since the MICRO-G ISS Flight Experiment is just entering the development phase, no experimental results have yet been collected. Prototype development will begin once the development phase funding starts. With prototype sensors available, initial 1-G data can be collected.

In anticipation of microgravity data, some simulations have been developed to predict the motion of an astronaut while floating freely. In the past, astronauts have demonstrated their microgravity movement skills by performing self-rotation techniques using only their arms and legs, demonstrating that it is possible to re-orient one's body with zero total angular momentum.

In order to verify that self-rotations are dynamically possible, a simple simulation was run that attempted to demonstrate this rotation technique. A joint Proportional-Derivative (PD) controller was used to achieve the initial angular displacement and to regulate the torso and legs back to alignment again. Figure 5 shows the absolute rotation angles of the torso and the legs and Figure 6 shows a frame from the movie generated to illustrate graphically what is happening.

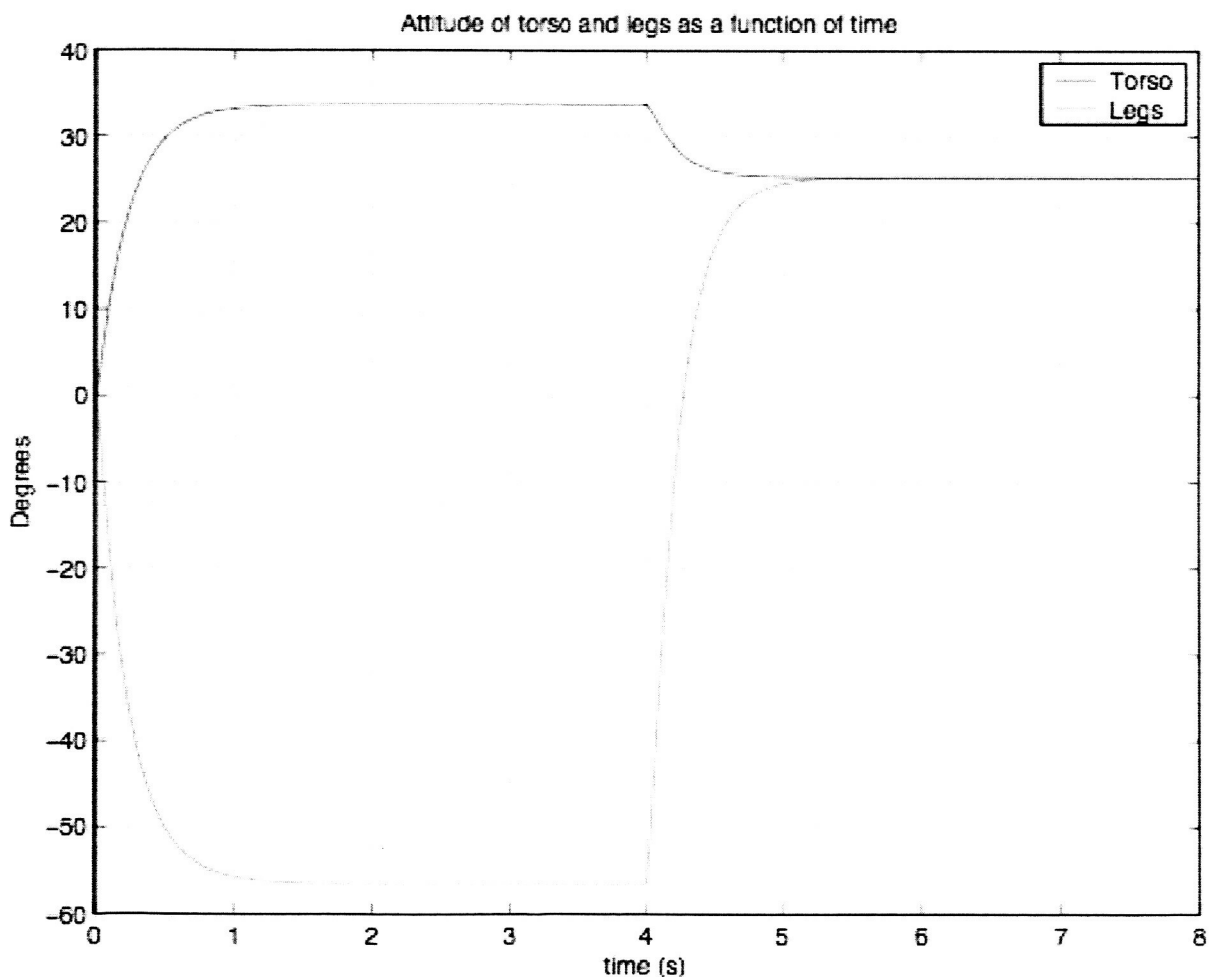


Figure 5: Plot showing the displacements of the torso and legs during a simulated astronaut self-rotation maneuver.

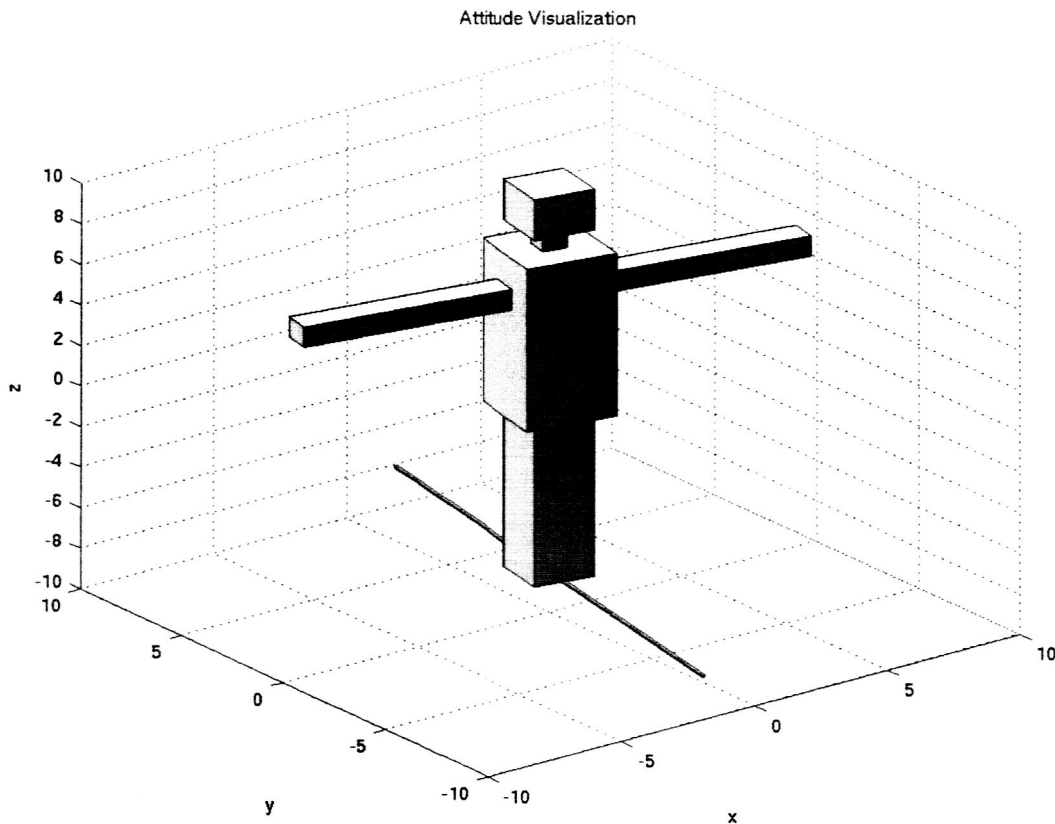


Figure 6: A frame taken out of the dynamic simulation of self-rotation of an astronaut.

Notice how in Figure 5, when the torso and legs re-align following an initial angular separation of 80 degrees, there is an angular displacement of about 25 degrees. We attempted this maneuver using a rotating chair and some small (4 lbs) weights. With practice, we were able to successfully perform the maneuver and achieve a net rotation of 25 degrees. Care needed to be taken to ensure that both the initial torso torque and the return torque were performed accurately yet rapidly to minimize the effect of friction in the chair (since friction can be used as a crutch to achieve greater rotations than would be possible in microgravity).

Other motions described in [Kulwicki et al., 1962] (such as the “lasso” maneuver) were also attempted in which arms mimic momentum wheels. While these also produced net rotations, they required much more work than the simple rotation outlined above.

Other simulations have focused on developing methods for estimating the joint torques exerted by the crew. Due to the strong non-linearity of multi-link dynamics, some advanced estimation techniques are required to estimate the joint torques. Techniques currently under investigation include the Unscented Kalman Filter (UKF) coupled with an optimization problem that solves for the most likely joint torques given the current estimates of joint positions, rates and accelerations.

Figure 7 shows the joint torque estimation results from a simple simulation of a person standing. To make this simulation more realistic, noise has been added to the joint angle and force plate measurements. Notice how the joint torque estimates closely follow the true joint torques used to produce the simulation. Current research is studying ways to reduce the estimation error through classical Kalman smoothing techniques.

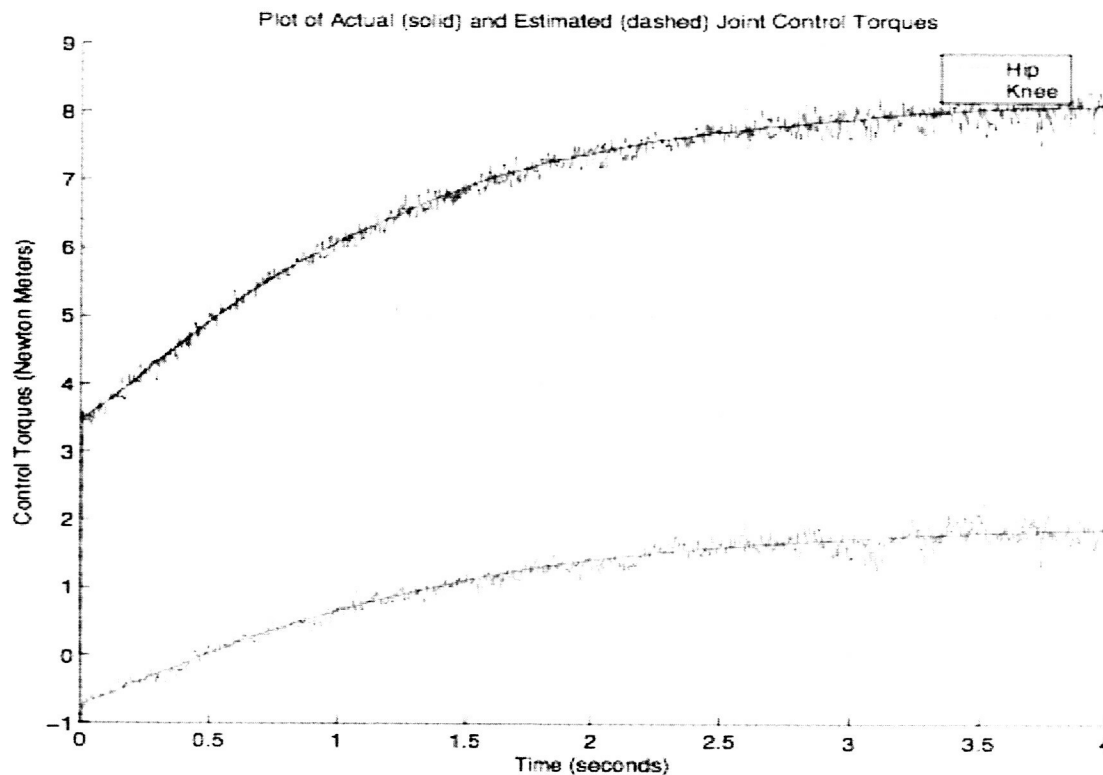


Figure 7: Plot of leg joint torques and corresponding joint estimates as a function of time for the hip (top line) and the knee (bottom line).

Expected Deliverables and Critical Path Roadmap Targeted Research:

- The MICR0-G effort will lead to improved crew training techniques and in-flight countermeasures based upon the observed adaptation of astronauts in altered gravity environments. These techniques and countermeasures will not only familiarize crewmembers with their environment in space, they will also begin the locomotor adaptation prior to exposure to another gravitational environment.[†]
- A biomechanical model that predicts the locomotor control strategies astronauts develop for a given gravitational environment and the adaptation process used to develop them. This model may include the ratio of muscle/joint usage as a function of time after exposure to the new environment and will be physics-based, accounting for realistic, dynamic human motions.[‡]
- A kinematic and kinetic capability for NASA that permits quantitative biomechanical analysis of astronaut full-body motions and performance using stereo or multiple cameras, instrumented crew restraints and custom software. The developed hardware and software will be delivered to NASA. The MICR0-G sensors and video analysis tools will provide the opportunity for countless other studies requiring detailed astronaut biomechanics and dynamics (e.g., exercise, disturbance of the μ G environment, sensorimotor adaptation and control.)[§]

[†] Addresses SHFE Risks #1 (Mismatch between crew physical capabilities and task demands - 1.4.4, 1.7.1, 1.7.3) and #2 (Mismatch between crew cognitive capabilities and task demands - 2.1.2, 2.4.3, 2.4.4).

[‡] Addresses SHFE Risk #1 (Mismatch between crew physical capabilities and task demands - 1.3.2, 1.8.1, 1.9.1, 1.9.2, 1.9.3, 1.11.2).

[§] Addresses SHFE Risk #1 (Mismatch between crew physical capabilities and task demands - 1.3.1, 1.4.1, 1.11.1).

Summary

The Experiment (ED) was written and presented in November 2003 and all MICRO-G proposed goals were met (Experiment #01-E077, Document #LS-20459). Both the Systems Requirements Review (SRR) and the Preliminary Design Review (PDR) are scheduled for October 2004 and test flights on the KC-135 microgravity aircraft are tentatively scheduled for January 2005.

The overall goal of this research program is to improve astronaut performance and efficiency through the use of rigorous quantitative dynamic analysis, simulation and experimentation. This goal will be achieved by studying the neural adaptation process that permits astronauts to efficiently perform movements across a spectrum of gravity (*i.e.*, microgravity, Moon, Mars, and Earth). Our progress in the past year has positioned us well to achieve and possibly exceed our goals for next year.

References

- [Baroni et al., 2001] G. Baroni, A. Pedrocchi, G. Ferrigno, J. Massion, and A. Pedotti. Static and dynamic postural control in long-term microgravity: evidence of a dual adaptation. *Journal of Applied Physiology*, 90:205–215, August 2001.
- [Kulwicki et al., 1962] P. V. Kulwicki and E. J. Schlei. Weightless Man: Self-rotation techniques. Technical Report AMRL-TDR-62-129, Behavioral Science Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio, 1962.
- [Newman et al., 1999] D. Newman, S. Beck, A. Amir, G. Baroni, G. Ferrigno, and A. Pedotti. Measuring astronaut performance in microgravity: Loads and modeling. In *Proceedings of the First Biennial Space Biomedical Investigators' Workshop*, League City, TX, January 1999.
- [Newman et al., 2001] D. J. Newman, A. R. Amir, and S. M. Beck. Astronaut-induced disturbances to the microgravity environment of the Mir space station. *Journal of Spacecraft and Rockets*, 38(4):578–583, August 2001.
- [Newman et al., 2000] D. J. Newman and D. Jackson. *Neural Control of Posture and Movement*, chapter 20, pages 282–291. Springer-Verlag, 2000.

Other Information and Materials

Presentations

Philip A. Ferguson, "Adaptation and Performance Analysis of Human IVA/EVA." Presented at the Habitation 2004 Conference, January 5, 2004 in Orlando, Florida.

Dava J. Newman, "MICRO-G Experiment Requirements Review (ERR)." Presented at the Johnson Space Center (JSC), November 15, 2003 in Houston, TX.

Dava J. Newman, "Considering Human Space Systems: from the International Space Station to Mars," K.D. Wood Colloquium Speaker, Dept. of Aerospace Engineering, University of Colorado at Boulder, CO. April 2004.

Abstracts

Philip A. Ferguson, Christopher E. Carr, Bradley Pitts and Dava J. Newman, "Adaptation and Performance Analysis of Human Motion During Intra- and Extra-vehicular Activities." *Submitted to and accepted by the Habitation 2004 Conference in Orlando, Florida, January, 2004.*

Philip A. Ferguson, Charles P. Coleman and Dava J. Newman, "Characterization of Human Locomotor Control Strategies and Adaptation Across a Spectrum of Gravitational Environments." *Submitted to and accepted by the 55th International Astronautical Congress to be held October 4-8, 2004 in Vancouver, British Columbia Canada.*

Supported Students

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